

# SPIN STRUCTURE FUNCTIONS OF THE NUCLEON\* <sup>†</sup>

Xiangdong Ji

*Center for Theoretical Physics*

*Laboratory for Nuclear Science*

*and Department of Physics*

*Massachusetts Institute of Technology*

*Cambridge, Massachusetts 02139*

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## Abstract

I begin with a general discussion about importance of constructing a picture of the nucleon in terms of QCD degrees of freedom, emphasizing the role of spin structure functions. I then give a short overview on the theoretical and experimental status of the spin structure of the nucleon. Following that, I mention several upcoming experiments to measure the flavor and sea structure in polarized quark distributions and the polarized gluon distribution  $\Delta g(x)$ . Finally, I discuss other spin-related physics, such as the polarizabilities of gluon fields  $\chi_B$  and  $\chi_E$ , the quark transversity distribution  $h_1(x)$ , and the spin structure functions  $G_1$  and  $G_2$  at low  $Q^2$ .

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## I. WHY ARE STRUCTURE FUNCTIONS INTERESTING?

The answer to the question is simple: The structure functions directly reflect the QCD degrees of freedom manifested by quarks and gluons. In the past three decades, our understanding of the nucleon structure has mainly come from models: the Constituent Quark Model, the Nambu-Jona-Lasinio Model, Bags, Strings, Hedgehogs, Instantons, Monopoles, to name just a few. These models are quite successful in explaining bulk properties of the nucleon. For instance, every model is made to fit the nucleon mass and most predicts correctly the anomalous magnetic moment. However, these models cannot explain more detailed aspects of the nucleon structure such as structure functions, because no one knows yet how to translate effective degrees of freedoms used in the models to quarks and gluons in QCD. [This is perhaps a bit of pessimistic in light of the many successes of models, like the quark models, in which a direct identification of QCD and constituent quarks is usually made. However, the right question to ask in QCD should be why the models are so successful, not why they fail occasionally.] For the same reason, the picture of the nucleon in QCD can be very different from that in a model. To illustrate this point, let me consider perhaps the most basic property of the nucleon: the mass.

The mass structure of the nucleon varies dramatically in different phenomenological models. In the constituent quark model, the mass is a sum of the three constituent quark masses plus a small amount of kinetic and potential energy. In the simplest version of the MIT bag model, the mass is a sum of kinetic energies for three quarks plus the vacuum energy of the bag. In QCD, a study of the energy-momentum tensor shows that the nucleon mass can be separated into four gauge-invariant parts [1],

$$M = M_q + M_m + M_g + M_a , \quad (1)$$

where  $M_q$  is the matrix element of  $\int d^3x \psi^\dagger (-i\boldsymbol{\alpha} \cdot \mathbf{D}) \psi$  and represents the contribution of quark kinetic and potential energies.  $M_m$  is the matrix element of  $\int d^3x \bar{\psi} m \psi$  and represents the contribution of quark masses.  $M_g$  is the matrix element of  $\int d^3x (\mathbf{E}^2 + \mathbf{B}^2)/2$  and represents the contribution of the gluon energy. Finally,  $M_a$  is the matrix element of  $\int d^3x (9\alpha_s/16\pi^2)(\mathbf{E}^2 - \mathbf{B}^2)$  and represents the contribution of the QCD trace anomaly [2].

Using the deep-inelastic scattering data on  $F_2$  [3] and the  $\pi - N$   $\sigma$  term and the second-order chiral perturbation calculation for the baryon-octet mass splitting [4], it was found that [1],

$$\begin{aligned} M_q &= 270 \text{ MeV}, & M_m &= 160 \text{ MeV}, \\ M_g &= 320 \text{ MeV}, & M_a &= 190 \text{ MeV} . \end{aligned} \quad (2)$$

Thus the quark kinetic and potential energies contribute only about a third of the nucleon mass. The quark masses contribute about one-eighth. The canonical gluon energy also contributes about a third. It was argued in Ref. [1] that the anomaly contribution is analogous to the vacuum energy in the MIT bag model. Since none of the phenomenological models gives a similar mass structure, it is difficult to relate the effective degrees of freedom with the QCD quarks and gluons in a straightforward way.

## II. THE SPIN STRUCTURE OF THE NUCLEON

The holy grail in studying the spin structure of the nucleon is to know how the spin of the nucleon is distributed among its constituents. Intuitively, one can write down the following decomposition of the nucleon spin,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g , \quad (3)$$

where  $\Delta\Sigma$  and  $\Delta g$  are helicities of quarks and gluons, and  $L_q$  and  $L_g$  are the quark and gluon orbital angular momenta.

In QCD, there is good news and bad news about this decomposition. The good news is that the separation has a field theoretical foundation, in the sense that each part can be identified with a matrix element of a quark-gluon operator. Indeed [5],

$$\begin{aligned} \Delta\Sigma &= \langle P+ | \int d^3x \bar{\psi} \gamma^3 \gamma_5 \psi | P+ \rangle , \\ \Delta g &= \langle P+ | \int d^3x (E^1 A^2 - E^2 A^1) | P+ \rangle , \\ L_q &= \langle P+ | \int d^3x i \psi^\dagger (x^1 \partial^2 - x^2 \partial^1) \psi | P+ \rangle , \\ L_g &= \langle P+ | \int d^3x E_i (x^2 \partial^1 - x^1 \partial^2) A_i | P+ \rangle . \end{aligned} \quad (4)$$

The bad news is that field theory is counter-intuitive. In fact,  $\Delta g$ ,  $L_q$  and  $L_g$  are neither separately gauge invariant nor Lorentz invariant, although their sum is. Furthermore, because composite operators in field theory are generally divergent, their matrix elements are scale-dependent after renormalization. The only component that is gauge invariant and frame-independent is the quark helicity contribution. The frame independence is obvious from the Lorentz structure of the matrix element. In the literature, there have been discussions about boosting the quark spin from rest to the infinite momentum frame. These discussions are irrelevant to the problem at hand.

It is easy to show that in the infinite momentum frame (or light-front coordinates) and light-like gauge ( $A^+ = 0$ )  $\Delta g$  is the first moment of the gluon helicity distribution  $\Delta g(x)$ , measurable in high-energy processes. For this reason, I will talk henceforth about the spin decomposition in the infinite momentum frame and light-like gauge.

The renormalization scale dependence can be calculated in perturbative QCD. For the quark and gluon helicities, the evolution in the leading-log approximation is the Altarelli-Parisi equation [6],

$$\frac{d}{dt} \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix} = \frac{\alpha_s(t)}{2\pi} \begin{pmatrix} 0 & 0 \\ \frac{3}{2}C_F & \frac{\beta_0}{2} \end{pmatrix} \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix} , \quad (5)$$

where  $t = \ln Q^2/\Lambda_{\text{QCD}}^2$ ,  $C_F = 4/3$  and  $\beta_0 = 11 - 2n_f/3$  with  $n_f$  the number of quark flavors. The solution of the equation is well-known,

$$\begin{aligned} \Delta\Sigma(t) &= \text{const} , \\ \Delta g(t) &= -\frac{4\Delta\Sigma}{\beta_0} + \frac{t}{t_0} \left( \Delta g_0 + \frac{4\Delta\Sigma}{\beta_0} \right) . \end{aligned} \quad (6)$$

Thus the gluon helicity grows logarithmically with the renormalization scale  $Q^2$ . To understand this physically, let us consider the splitting of a helicity +1 gluon. There are four possible splitting products: 1) a quark with helicity 1/2 and an antiquark with helicity -1/2; 2) a quark with helicity -1/2 and an antiquark with helicity 1/2; 3) a gluon with helicity +1 and another with helicity -1; 4) two gluons with helicity +1. In the first two processes there is a loss of the gluon helicity with a probability  $(n_f/2) \int_0^1 dx (x^2 + (1-x)^2)$ . In the third process there is a loss of gluon helicity with a probability  $\int_0^1 dx (x^3/(1-x) + (1-x)^3/x)$ . And in the last process there is an increase of gluon helicity with a probability  $\int_0^1 dx 1/(x(1-x))$ . The total helicity change in one gluon splitting is  $11/2 - n_f/3 > 0$ . Thus the gluon helicity increases without bound as one probes increasingly smaller distance scales.

The evolution of the quark and gluon orbital angular momenta was first recognized and discussed by Ratcliffe [7]. However, the discussion is incomplete and contains a mistake. Recently, Tang, Hoodbhoy and I derived the following equation [8],

$$\frac{d}{dt} \begin{pmatrix} L_q \\ L_g \end{pmatrix} = \frac{\alpha_s(t)}{2\pi} \begin{pmatrix} -\frac{4}{3}C_F & \frac{n_f}{3} \\ \frac{4}{3}C_F & -\frac{n_f}{3} \end{pmatrix} \begin{pmatrix} L_q \\ L_g \end{pmatrix} + \frac{\alpha_s(t)}{2\pi} \begin{pmatrix} -\frac{2}{3}C_F & \frac{n_f}{3} \\ -\frac{2}{3}C_F & -\frac{11}{2} \end{pmatrix} \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix} . \quad (7)$$

If one knows the nucleon spin composition at a perturbative scale  $Q_0^2$ , one can get the spin composition at any other perturbative scale by solving these equations. As  $Q^2 \rightarrow \infty$ , the solution becomes especially simple,

$$\begin{aligned} L_q + \frac{1}{2}\Delta\Sigma &= \frac{1}{2} \frac{3n_f}{16 + 3n_f} , \\ L_g + \Delta g &= \frac{1}{2} \frac{16}{16 + 3n_f} . \end{aligned} \quad (8)$$

Thus the partition of the nucleon spin between quarks and gluons follows the well-known partition of the nucleon momentum [9]! If the  $Q^2$  evolution is slow, then it predicts that quarks carry only about 50% of the nucleon spin even at low momentum scales.

Given these theoretical comments, let us now consider the experimental status. In the past several years, EMC/SMC and E142/143 experiments have established conclusively that [10]

$$\Delta\Sigma(Q^2 \sim 10\text{GeV}^2) \sim 0.3 \pm 0.07 , \quad (9)$$

that is, about 70% of the nucleon spin is carried by  $\Delta g$ ,  $L_q$  and  $L_g$ . If slow  $Q^2$  variation is true, one expects the quark orbital angular momentum also carries about 10% to 30% of the nucleon spin. Using SU(3) symmetry and the hyperon  $\beta$  decay data, it was determined that [11],

$$\begin{aligned} \Delta u &= 0.83 \pm 0.03 , \\ \Delta d &= -0.43 \pm 0.03 , \\ \Delta s &= -0.10 \pm 0.03 . \end{aligned} \quad (10)$$

Thus it seems that about 10% of the spin is carried by the strange flavor. However, there are arguments in the literature that the SU(3) symmetry breaking can change this number significantly [12].

What are the future opportunities in studying the spin structure of the nucleon? First of all, we would like to find flavor separation and sea quark polarization. An independent determination of the flavor separation can test the validity of SU(3) symmetry in the hyperon  $\beta$ -decay data. The size of the sea quark polarization might be the key to understand the smallness of  $\Delta\Sigma$ . At present time, there are two experiments which promise to study in detail the flavor and sea structure. First is the HERMES experiment at HERA [13]. Motivated by an idea by Frankfurt et al. and Milner and Close [14], the HERMES experiment plans to study the pion production in

$$\vec{e} + \vec{P} \rightarrow e' + \pi + X . \quad (11)$$

Define the production asymmetry according to,

$$A_{LL} = \frac{N_{\uparrow}^{\pi^+-\pi^-}(x) - N_{\downarrow}^{\pi^+-\pi^-}(x)}{N_{\uparrow}^{\pi^+-\pi^-}(x) + N_{\downarrow}^{\pi^+-\pi^-}(x)} , \quad (12)$$

where  $N_{\uparrow\downarrow}^{\pi^+-\pi^-}$  is the number of  $\pi^+$  minus the number of  $\pi^-$  produced in the current fragmentation region when the nucleon target is polarized. It is simple to show in the simple parton model that,

$$A_P = \frac{4\Delta u^v(x) - \Delta d^v(x)}{4u^v(x) - d^v(x)}; \quad A_D = \frac{\Delta u^v(x) - \Delta d^v(x)}{u^v(x) - d^v(x)} , \quad (13)$$

where  $A_P$  and  $A_D$  refers to asymmetries for proton and deuteron targets, respectively. Thus by measuring these, one can determine the valence polarizations of the up and down quarks separately.

The second experiment is at polarized RHIC, where one can study polarized proton collisions [15]. By measuring the single spin asymmetry in  $W^\pm$  boson production,

$$A_L^{W^+} = \frac{\Delta u(x)\bar{d}(y) - \Delta\bar{d}(x)u(y)}{u(x)\bar{d}(y) + \bar{d}(x)u(y)} . \quad (14)$$

with  $u \leftrightarrow d$  for  $A_L^{W^-}$ , one can extract quark and antiquark helicity distributions independently. The Drell-Yan process with fixed targets also offers an interesting opportunity in this direction [17].

The polarized gluon distribution yields information on the gluon helicity contribution to the nucleon spin. Nothing is known about it yet experimentally. Not much is known theoretically, except there are arguments that  $\Delta g$  is probably positive. From QCD perturbation theory in which a positive helicity quark is more likely to produce a positive helicity gluon, Brodsky, Burkardt and Schmidt proposed a polarized gluon distribution [18],

$$\Delta g(x) = \frac{35}{24}[1 - (1-x)^2](1-x)^4 \quad (15)$$

which yields  $\Delta g = 0.54$ . Jaffe has recently calculated  $\Delta g$  from the MIT bag model. He argued that the positive sign is related to  $N - \Delta$  splitting [19]. It is peculiar though that his result comes entirely from the bag boundary!

Experimentally, one can probe the gluon distribution through both deep-inelastic electron scattering and hadron-hadron scattering. In the former process, one can learn about the gluon distribution through  $Q^2$ -evolution of  $g_1$  structure function, two-jet production, or  $J/\psi$  production. These experiments can be done in polarized HERA or future ELFE machine. It seems to me that extracting  $\Delta g$  from these processes is quite difficult due to high demanding for statistics. A better place to learn about the gluon polarization may be at RHIC, where one can measure  $\Delta g$  in a more direct way, for instance, through jet cross section, direct photon production, or gluon fusion processes [15].

### III. OTHER SPIN-RELATED PHYSICS

In this part, I discuss three topics that are related to the polarized nucleon. First is the polarizabilities of the color electric and magnetic fields when the nucleon is at its rest frame. Second is the quark transversity distribution in a transversely polarized nucleon. and finally, the spin-dependent structure function  $G_1$  and  $G_2$  at and near  $Q^2 = 0$ .

1). **Polarizabilities of Color Fields.** If a nucleon is polarized in its rest frame with polarization vector  $\mathbf{S}$ , how do the color fields inside of the nucleon respond? Intuitively, due to parity conservation, the color magnetic field orients in the same direction as the polarization and the color electric field in the direction perpendicular to it. In QCD, one can define the following polarizabilities of color fields [20],

$$\begin{aligned}\langle PS|\psi^\dagger g\mathbf{B}\psi|PS\rangle &= 2\chi_B M^2 \mathbf{S} , \\ \langle PS|\psi^\dagger \boldsymbol{\alpha} \times g\mathbf{E}\psi|PS\rangle &= 2\chi_E M^2 \mathbf{S} ,\end{aligned}\tag{16}$$

How to measure  $\chi$ 's? This can be done in the polarized electron scattering where the struck quark absorbs the virtual photon and propagates in the background color fields of the nucleon. The effects of color fields are the final state interactions (FSI). Here we have a unique situation that the FSI helps us to learn about the properties of the nucleon, unlike in many other cases in nuclear physics where FSI is entirely a nuisance.

In the polarized electron scattering, one measures two spin-dependent structure functions  $G_1$  and  $G_2$ , defined through the antisymmetric part of the hadron tensor,

$$\begin{aligned}W_{\mu\nu}^A &= \frac{1}{4\pi} \int d^4\xi e^{i\xi\cdot q} \langle PS|J_{[\mu}(\xi)J_{\nu]}(0)|PS\rangle \\ &= -i\epsilon_{\mu\nu\alpha\beta} q^\alpha \left[ S^\beta \frac{G_1}{M^2} + (\nu M S^\beta - (S\cdot q)P^\beta) \frac{G_2}{M^4} \right] ,\end{aligned}\tag{17}$$

In the deep-inelastic limit, define two scaling functions  $g_1 = (\nu/M)G_1$  and  $g_2 = (\nu/M)^2 G_2$ . According to operator product expansion, we have [21,22] ,

$$\begin{aligned}\int_0^1 g_1(x, Q^2) dx &= \frac{1}{2} \sum_f e_f^2 a_{0f} C_{0f}(\alpha_s) + \frac{M^2}{9Q^2} \sum_f e_f^2 \left[ C_{2f}(\alpha_s) a_{2f} \right. \\ &\quad \left. + 4\tilde{C}_f(\alpha_s) d_{2f} - 4\tilde{\tilde{C}}_f(\alpha_s) f_{2f} \right] + \dots \\ \int_0^1 g_2(x, Q^2) x^2 dx &= \frac{1}{3} \sum_f e_f^2 d_{2f} \tilde{C}_f(\alpha_s) - \frac{1}{3} \sum_f e_f^2 a_{0f} C_{0f}(\alpha_s) + \mathcal{O}\left(\frac{M^2}{Q^2}\right) ,\end{aligned}\tag{18}$$

where  $a_{0f}$  and  $a_{2f}$  are the matrix elements of the twist-two, spin-one and spin-three operators, respectively. The index  $f$  sums over quark flavors.  $C_f$ 's ( $1 + \mathcal{O}(\alpha_s)$ ) are coefficient functions summarizing QCD radiative corrections.  $d_2$  and  $f_2$  are the matrix elements of some twist-three and four operators, respectively. Knowing these two matrix elements, one can immediately calculate the polarizabilities,

$$\begin{aligned}\chi_B &= \frac{1}{3}(4d_2 + f_2) , \\ \chi_E &= \frac{2}{3}(2d_2 - f_2) .\end{aligned}\tag{19}$$

Let me now quote some numbers. From the recent E143 data, it was determined [23]

$$d_2^p = 0.0054 \pm 0.005, \quad d_2^d = 0.004 \pm 0.009 .\tag{20}$$

On the other hand, the bag model calculation yields [22,24],

$$d_2^p = 0.010, \quad d_2^n = 0.0 .\tag{21}$$

which is consistent with the experimental data. The QCD sum rule calculations yield [25],

$$d_2^p = -0.006 \pm 0.003, \quad d_2^n = -0.017 \pm 0.005 .\tag{22}$$

And finally a recent calculation in quenched lattice QCD gives [26],

$$d_2^p = -0.048 \pm 0.005, \quad d_2^n = -0.005 \pm 0.003 .\tag{23}$$

Surprisingly, both the sum rule and lattice calculations have difficulty in confronting experimental data.

2). **Quark Transversity Distribution.** Consider a transversely-polarized nucleon moving in the  $z$  direction. Using  $q_l(x)$  and  $q_\uparrow(x)$  to denote the quark densities with polarizations  $|\uparrow\downarrow\rangle = (|+\rangle + |-\rangle)/\sqrt{2}$  where  $|\pm\rangle$  are the helicity states of quarks. Then the transversity distribution is defined as

$$h_1(x) = q_\uparrow(x) - q_\downarrow(x) .\tag{24}$$

This distribution was first introduced by Ralston and Soper [27] in studying polarized Drell-Yan collisions and further studied by Artru and Mekfi [28], Jaffe and Ji [29], and others.

$h_1(x)$  is a chiral-odd distribution, i.e. a correlation between left- and right-handed quarks. As such, it cannot appear in inclusive deep-inelastic scattering process. So far, two different methods have been proposed to measure  $h_1(x)$ . First is through the asymmetry in the pion production in longitudinally polarized electron scattering on a transversely polarized nucleon target [30]. The second is through the asymmetry in Drell-Yan and  $Z^0$ -boson production from quark and antiquark annihilations in polarized proton-proton scattering [27–29,16].

One of the most interesting aspects of  $h_1(x)$  is the sum rule. It was shown by Jaffe and Ji that  $h_1(x)$  obeys the following sum rule,

$$\int_0^1 dx (h_1(x) - \bar{h}_1(x)) = \delta q .\tag{25}$$

where  $\delta q$  is the tensor charge of the nucleon, defined in terms of the nucleon matrix element of the tensor current. It is easy to shown that in non-relativistic quark models, the tensor charge is equal to the axial charge. In the MIT bag model, it was determined that  $\delta u = 1.17, \delta d = -0.29$  [31]. On the other hand, the QCD sum rule calculation yields  $\delta u = 1.00 \pm 0.5$  and  $\delta d = 0.0 \pm 0.5$  [31]. And more recently, the calculation in the chiral soliton model produced  $\delta u = 1.07$  and  $\delta d = -0.38$  [32].

3).  **$G_1$  and  $G_2$  Structure Functions Near and At  $Q^2 = 0$ .** This is mostly about CEBAF physics. Due to time (and space) limitations, I just briefly mention a few important topics in this direction. It is interesting to test the Drell-Hearn-Gerasimov(DHG) sum rule derived many years ago [33],

$$\int_{\nu_{\text{th}}}^{\infty} \frac{d\nu}{\nu} [\sigma_{3/2} - \sigma_{1/2}] = \frac{2\pi^2 \alpha_{\text{em}}}{M^2} \kappa^2, \quad (26)$$

where the  $\sigma_{1/2,3/2}$  refer to the inclusive photo-production cross sections with total helicities 1/2 and 3/2, respectively, along the photon momentum axis.  $\kappa$  is the anomalous magnetic moment of the nucleon. Several experiments proved at CEBAF will be relevant to such test [34]. It is also interesting to measure the spin polarizability defined as the next moment of the photon-production cross section difference,

$$\gamma = -\frac{1}{4\pi^2} \int_{\nu_{\text{th}}}^{\infty} \frac{d\nu}{\nu^3} [\sigma_{3/2} - \sigma_{1/2}], \quad (27)$$

and to compare it with chiral perturbation calculation [35]. A third topic is to study  $Q^2$  dependence of  $G_1$  sum rule. Defining,

$$\Gamma(Q^2) = \frac{Q^2}{2M^2} \int_{Q^2/2}^{\infty} G_1(\nu, Q^2) \frac{d\nu}{\nu}, \quad (28)$$

one can expand at low- $Q^2$  [22],

$$\Gamma(Q^2) = 1.396 - 8.631Q^2 + \alpha Q^4 + \dots. \quad (29)$$

The first two terms are known from elastic scattering properties of the nucleon and the DHG sum rule. It is possible to calculate the coefficient  $\alpha$  in low-energy theories, like chiral-perturbation theory. Again, one can test the calculation by measuring the  $Q^2$  dependence of the generalized DHG sum rule. Finally, I would like to mention the hadronic contribution to hyperfine splitting of hydrogen atom, which is a complicated integral of  $G_1$  and  $G_2$  structure functions at low  $Q^2$  [36]. Recently, P. Unrau has made an estimate of the contribution and found it at the level of 0.5 ppm [37]. With better knowledge of  $G_1$  and  $G_2$ , one hopes to compute the contribution at a better precision.

#### IV. SUMMARY AND CONCLUSION

I believe the goal of this field is to study and eventually understand the structure of hadrons in terms of QCD degrees of freedom: quarks and gluons. In this regard, much



progress has been made in the last few years. Experimentally, we have tested the Bjorken sum rule at the ten percent level, an important check on our understanding of experiments and QCD analysis. We have measured with good precision the quark helicity contribution to the nucleon spin. Theoretically, we now know how to generalize operator production expansion to any hard scattering process, to classify quark and gluon distribution functions, and to calculate perturbative corrections at the first few orders. However, much lies ahead of us. We would like to understand better the flavor and sea separation of quark helicity distributions. We would like to know the polarized gluon distribution. We need to measure the higher twist effects to better accuracy. We shall study systematically at CEBAF  $G_1$  and  $G_2$  structure functions at low  $Q^2$ . Finally, there is a lot to learn from hadron final states. Thus, I conclude that in the area of spin physics these are exciting times.

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